

“Grandeur in this view of life”: N-body simulation models of the Galactic habitable zone

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Abstract

We present an isolated Milky Way-like simulation in GADGET2 N-body SPH code. The Galactic disk star formation rate (SFR) surface densities and stellar mass indicative of Solar neighbourhood are used as thresholds to model the distribution of stellar mass in life friendly environments. SFR and stellar component density are calculated averaging the GADGET2 particle properties on a 2D grid mapped on the Galactic plane. The peak values for possibly habitable stellar mass surface density move from 10 to 15 kpc cylindrical galactocentric distance in 10 Gyr simulated time span. At 10 Gyr the simulation results imply the following. Stellar particles which have spent almost all of their life time in habitable friendly conditions reside typically at ~ 16 kpc from Galactic centre and are ~ 3 Gyr old. Stellar particles that have spent $\geq 90\%$ of their 4 – 5 Gyr long life time in habitable friendly conditions, are also predominantly found in the outskirts of the Galactic disk. Less than 1% of these particles can be found at a typical Solar system galactocentric distance of 8 – 10 kpc. Our results imply that the evolution of an isolated spiral galaxy is likely to result in galactic civilizations emerging at the outskirts of the galactic disk around stellar hosts younger than the Sun.

1 Introduction

Boosted by the recent discoveries of the ever increasing number of extrasolar planets and their candidates (Howard, 2013), Galactic habitability studies are

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gaining momentum and are becoming an important part of the mainstream astrobiological research (Spitoni, Matteucci & Sozzetti, 2014; Dayal et al., 2015; Forgan et al., 2015). Apart from Earth, biospheres still remain unobserved, both inside and outside the Solar System. The absence of the empirical data causes an extreme difficulty for the robust studies on the evolution of living matter in the Universe. This is not likely to change until the arrival of the capacity to detect biomarkers from interstellar distances in various extrasolar planetary systems across the Galaxy. Since the matter in the Universe is primarily organized into galaxies, the evolution of life in the Universe will strongly correlate with the evolution of galaxies.

The present computing capabilities to simulate Galactic evolution can be very useful for understanding the significance of different Galactic processes in shaping the spatio-temporal distributions of Earth-like habitats. Following the introduction of the Galactic Habitable Zone (GHZ) concept (Gonzalez, Brownlee & Ward, 2001) we have further developed a general idea what are the basic preconditions for terrestrial-like habitats to appear and remain habitable. Apart from the chemical evolution, galactic dynamics can be of great importance for habitability in spiral galaxies due to radial population mixing (Roškar et al., 2011, 2008). This can significantly influence the distribution of habitable systems in the Galactic disk. In the previous numerous models of the Galactic habitability and SETI-oriented studies (i.e., Lineweaver, Fenner & Gibson, 2004; Gowanlock, Patton & McConnell, 2011; Forgan, 2009; Cotta & Morales, 2009; Prantzos, 2013; Vukotić & Čirković, 2012), stellar dynamics was not accounted for until the recent work of Forgan et al. (2015). The main goal of this paper is to determine the allowed habitable times forced upon the stellar systems from star formation rate (SFR) and stellar density as the global habitability agents in the Galaxy. We present and analyse an N-body SPH simulation of a single isolated Milky Way-like galaxy in order to model the spatio-temporal distribution of stellar mass in life friendly environment.

This has even wider scientific and methodological importance. In the famous last paragraph of "The Origin of Species" Darwin (1859) contrasted apparent simplicity of Newton's law of gravity and the consequent Keplerian motion of planets with the ecological complexity of "an entangled bank" created by biological evolution. In the very last sentence, however, he affirmed the underlying idea that *both* these aspects of nature, astronomical and biological, are explicable in the naturalistic terms by law-like dynamical regularities – and that we find "grandeur in this view of life" evolving from simple to multiple complex forms. The quantitative sort of astrobiological work as presented here is, in more than one sense, honouring and continuation of this Darwinian programme.

In the rest of this introductory section we describe the basic habitability factors that are considered in analysis of our simulation. Simulation is described in Section 2, details of the model are given in Section 3, while discussion and summary of the results are given in sections 4 and 5, respectively.

1.1 Habitability agents

Explosions of nearby supernovae are likely to be hazardous for a life dwelling planet up to a few pc distance (Gehrels et al., 2003) or even up to a kpc (Karam, 2002). At Galactic distance scales they can be considered as a local phenomena and their life hazard potential treated accordingly. An overall danger from a supernova is likely to be smaller compared to a stellar collision induced hazards and an occasional stress from a nearby supernovae can even boost the biological evolution (Filipović et al., 2013). However, a planetary system in the midst of a star forming region characterized by a high supernovae rate is likely to be hindered from developing a "fruitful" biosphere.

Continuity of habitable conditions is a necessity prerequisite for a planet to develop a versatile biosphere. Although minor dynamically stable changes can be suspended with plate tectonics feed-back cycles, any sufficiently large perturbation can push the planet outside the habitable temperature range without the possibility to recover. (It has almost happened on Earth as well during at least two "Snowball Earth" episodes during the Precambrian supereon.) A habitable planet should thus be as close as possible to a circular orbit around its host star. For multiple stellar systems, configurations with widely separated stellar components (where a planet is mostly bound and in proximity of a single stellar object) or very close in (where a planet revolves around multiple stellar host) are preferred. In crowded regions of the Galactic disk a frequent nearby passages (at a distances of ~ 100 AU) of neighbouring stars may cause a large stress on the orbits of their planets, either by disruption of planetary orbits or by perturbation of cometary and asteroidal belts. This can cause a life-devastating flux of impactors. In close enough encounters a large perturbation can even permanently push the planet outside circumstellar habitable zone or set it free from the host stellar system gravitational grasp.

Changes in the atmosphere of a life bearing planet, caused by a nearby stellar explosion or a stellar collision caused orbital disruption, might turn a planet into a "snowball", or a Venus-like world. Of course, this does not mean that the planet will become completely lifeless. Extremophiles, such as a single cell organisms that live in extreme conditions here on Earth, can still be present. However, the potential for evolution of life on such a planet would probably be severely constrained due to a very small number of ecological niches available (Morris, 2003). Such a fair biosphere is less likely to produce a complex intelligent species, detectable via interstellar travel, distant communication and other means, such as IR excess from dissipated energy (Zackrisson et al., 2015). There are multiple reasons to believe that evolution of cognition and intelligence is possible only within a large and diverse habitats, where many necessary evolutionary innovations could be achieved (Russell, 1995; Vermeij, 2006; Morris, 2011). It is unlikely to happen in tightly constrained, ultra-specialized habitats.

It is quite obvious that the existence of rocky planets is conditional upon presence of their building blocks in the interstellar matter, metals. Apart from heavy nuclei that sink down to cores of planetary objects during the cooling stage of their formation, medium weight metals such as silica, magnesium, car-

bon, nitrogen, oxygen, etc, are main constituents of mantle and crust. At first look it seems that higher metallicity of interstellar matter will yield higher number of rocky planets, but this need not be the case. The "goldilocks" approach taken by Lineweaver (2001); Peña-Cabrera & Durand-Manterola (2004) relies on the assumption that high metallicity is likely to lead to formation of gas giants with rocky cores, preferentially via core accretion model (see also, Buchhave et al., 2012; Ikoma, Nakazawa & Emori, 2000). The samples of exoplanets show that the highest number of discovered systems have hosts with near Solar metallicity. While this strongly favours habitability in the "goldilocks" manner, the existence of correlation between metallicity and the number of discovered rocky planets is far from clear since there are strong selection effects in play. Recent theoretical results indicate that planet formation starts at lower values of metallicity than previously assumed, already at $Z \geq 0.1 Z_{\odot}$ (Johnson & Li, 2012). The small number of discovered Earth-like planets and higher probability of detecting gas giants with current observational techniques are main reasons to question the existence of such a correlation (see Prantzos, 2008, and references therein). For the purpose of our model we constrain the metallicity of the possible stellar particles considered for habitability to be above the lowest determined values for existing samples of Earth-like exoplanets.

2 Simulation details

Following the model presented in Springel & Hernquist (2003), a small-scale simulation of an individual star-forming disk galaxy in GADGET2 code (Springel, Yoshida & White, 2001; Springel et al., 2005) was performed. The halo was set up in isolation following the approach taken by Navarro, Frenk & White (1997), with the gas and dark matter initially in virial equilibrium, known as the Navarro, Frenk & White (NFW) halo:

$$\frac{\rho(r)}{\rho_c} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}, \quad (1)$$

where r_s is the halo scale radius, δ_c is a characteristic (dimensionless) density, and $\rho_c = 3H^2/8\pi G$ is the cosmological critical density. The conventional parameter in this kind of model (Binney & Tremaine, 2008) is known as r_{200} , which is the distance from the centre of the halo at which the mean density is 200 times the ρ_c . The mass interior $M_{200} = 200 \frac{4}{3} \pi r^3 \rho_c$ was chosen to be $M_{200} = 10^{12} M_{\odot}$, being baryonic 10% of the mass. For the halo concentration factor $c = r_{200}/r_s$ a value of $c = 9.0$ was chosen. To describe the initial angular momentum J of the halo, the spin parameter $\lambda = \frac{J|E|^{1/2}}{GM_{\text{vir}}^{5/2}}$ is usually used. To produce a large disk, a value of the spin parameter $\lambda = 0.1$ was chosen.

For the purpose of simulating radial migrations in the galactic disk Roškar et al. (2008) used gas particles of $10^5 M_{\odot}$ and stellar particles of $3 \times 10^4 M_{\odot}$. In the initial conditions, we use 10^6 gas particles with a mass resolution of $10^5 M_{\odot}$. The gravitational softening length was set to 0.8 kpc for both, gas and stellar

particles. We include radiative cooling (Katz, Weinberg & Hernquist, 1996) and recipes for star formation and stellar feedback as described in Springel & Hernquist (2003). Each gas particle can produce up to two stellar particles of $5 \times 10^4 M_\odot$; When a gas particle produces the second stellar particle it is used up and is not in the simulation any more. A fixed metallicity value is assigned to the stellar particles equal to the metallicity of their gas particle progenitor at the time when the stellar particle is produced. After a 10 billion years simulation, there were 1055078 stellar particles, and 488158 gas particles. We sampled a 1000 snapshots from the simulation which translates into a 10^7 yr time resolution.

3 Habitability model

There are $\sim 10^{11}$ stellar systems in a typical L_* galaxy. Even with the developed computing hardware of today, N-body simulations of more than $\sim 10^7$ particles are a very rare occurrence. Usual mass resolution for a stellar component is in the $10^4 - 10^6 M_\odot$ interval. At present level of available computing resources it is not possible to make a full scale N-body simulation of the Galaxy with mass resolution at the level of the individual stellar systems. This makes it difficult to estimate the habitability of the individual stellar system. The global Galactic parameters such as SFR or stellar density can be modelled and calculated with high fidelity. Still, it is not possible to track the individual stellar system during the simulation and examine its position for an environmental habitability. At the level of resolved stellar mass, in a typical N-body simulation of the galaxy, stellar particles usually have masses of $\sim 10^5 M_\odot$. This is more representative of a stellar cluster, and that mass should be considered as smeared out rather than concentrated in a given position of the stellar particle.

The habitability of the stellar particles (see section 2) is calculated from the relevant Galactic parameters on a spatial 2D grid. The grid is mapped on the Galactic disk (xy plane in the simulation xyz coordinates). The 2D model requires less computation time than a more realistic 3D approach. Also, the results representation is straightforward since the plane of the disk is represented by the plotting plane. A significant precision improvement cannot be achieved with the 3D approach at the current level of the simulation performance, since the softening length in our simulation is of the order of thick disk thickness.

The SFR for each grid cell is estimated as the sum of the SFRs of the individual gas particles located within the cell. In a similar fashion a density of stellar (and gaseous) component is estimated from stellar (gas) particles found in a grid cell at the moment of calculation. The resulting surface densities for SFR, stellar and gaseous mass, are given in Figures 3, 1 and 2 respectively. It is evident that the star formation activity closely matches the dense gas areas. Since the modelled Galaxy is isolated, after about 3 Gyr SFR significantly drops. At latter times the areas of intense star formation are not solely found in the bulge of the Galaxy and inner disk but are drifting towards the disk outskirts as an expanding arms of the fading spiral pattern. The inner disk is thus left with

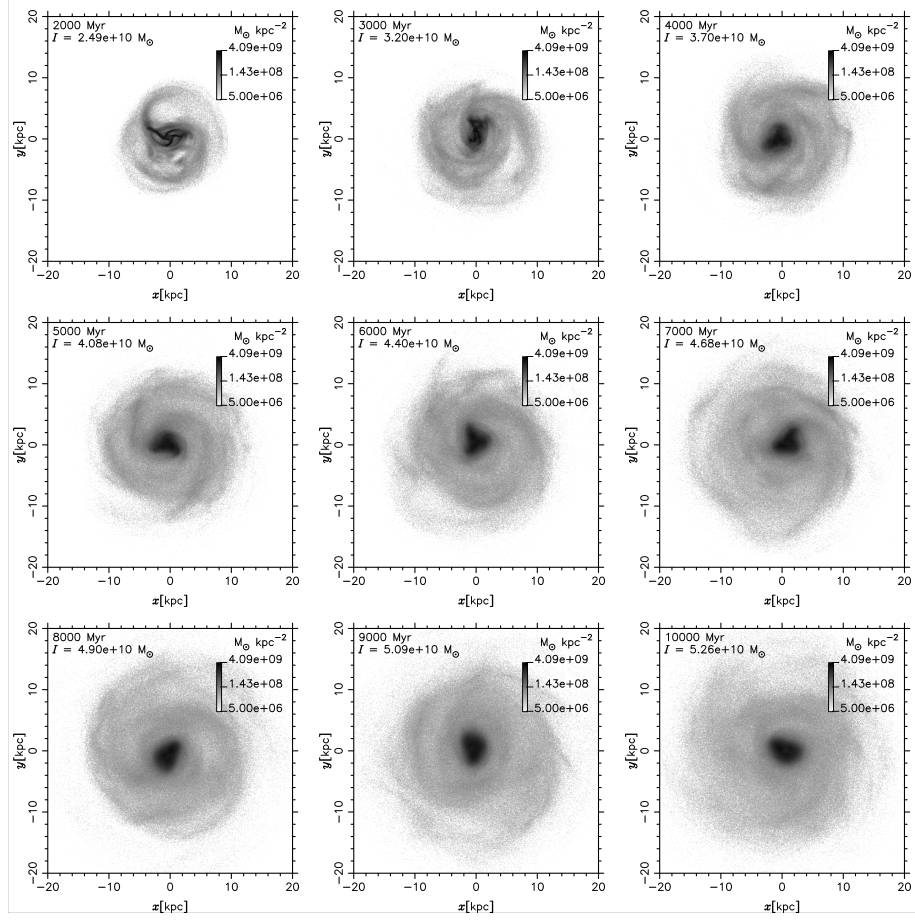


Figure 1: Stellar mass surface density. The time instant and integrated value for the given plotting range are indicated in each panel.

little to no areas of the intense star formation. Unlike gas, very dense areas of the stellar component are confined to vicinity of the Galactic Centre at all times. The denser areas in the disk arise as a loose spiral pattern that is expanding as more particles from the interior drift away. This gradually expands the stellar disk from ~ 10 to ~ 15 kpc.

We constructed an analytical habitability recipes to quantify the habitability relevant properties of the Galactic disk. These recipes are applied on the simulation data. In the remainder of this section this “post-simulation” analysis of ours is described in detail.

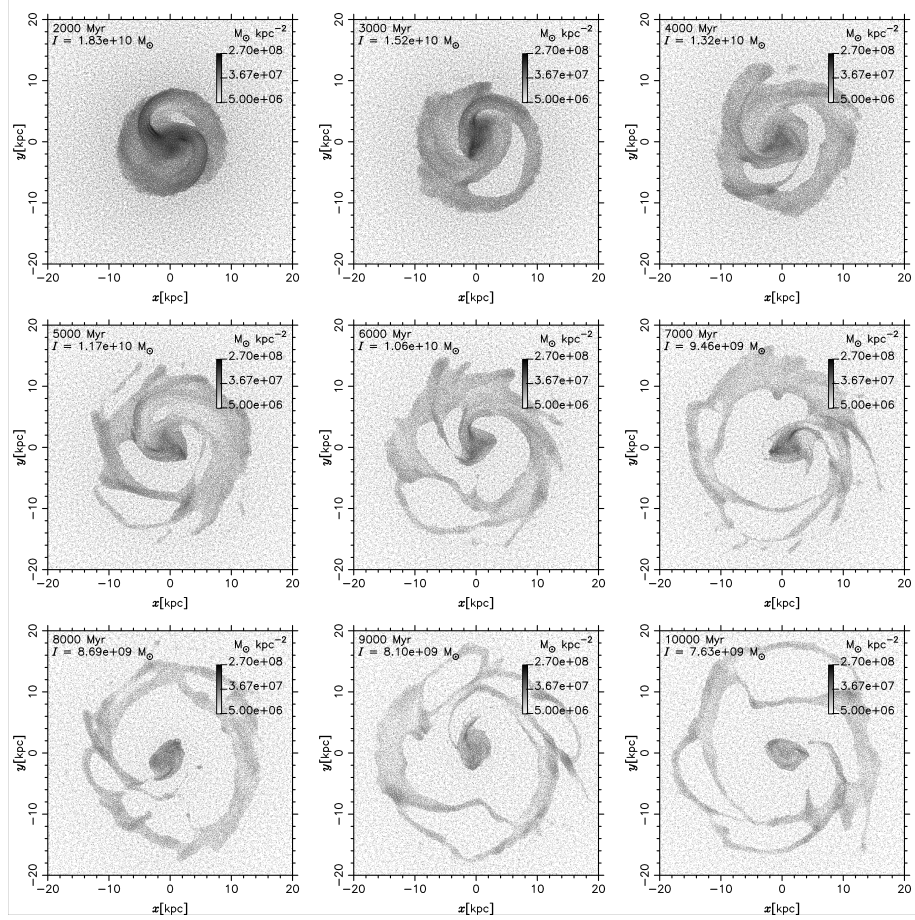


Figure 2: Gaseous mass surface density. The time instant and integrated value for the given plotting range are indicated in each panel.

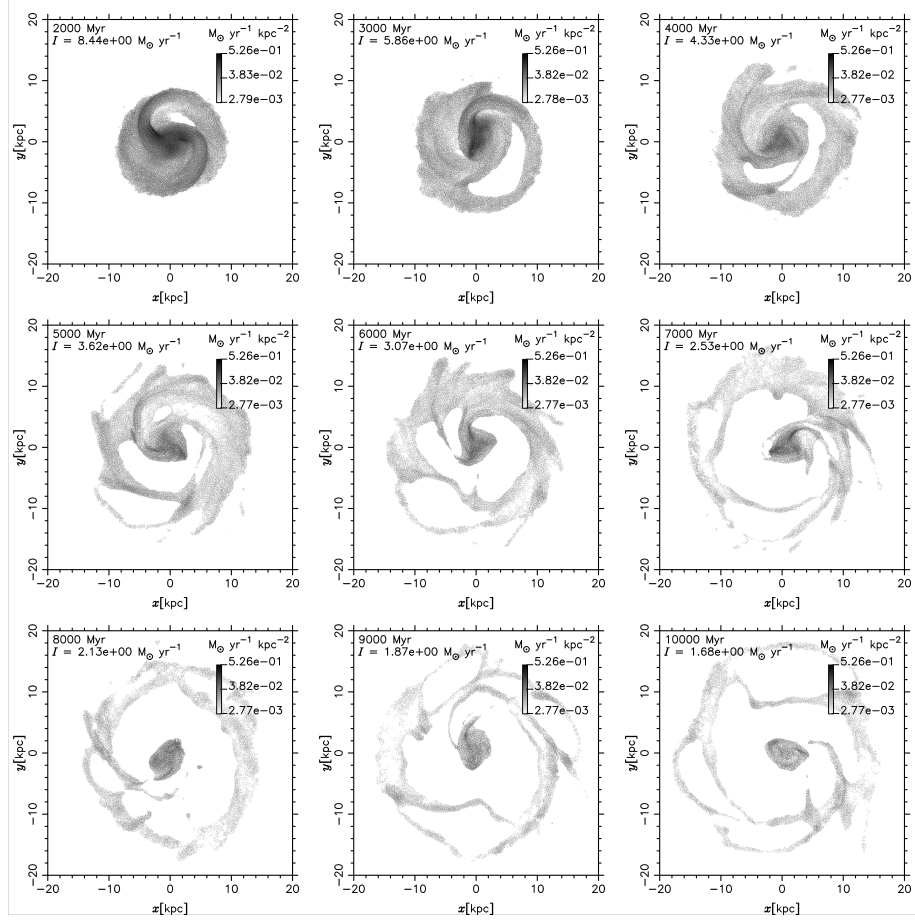


Figure 3: Star formation rate. The time instant and integrated value for the given plotting range are indicated in each panel.

3.1 Habitable environment

The habitability relevant parameters are calculated from the characteristics of the individual particles on a 400×400 grid in the XY simulation coordinate plane. The grid resolution is 100 pc and 100 pc along the x and y-axis, respectively. The grid cells are considered as the habitable friendly environment for the particles within them, if calculated values for the stellar number density are below $6.1 \times 10^7 \text{ M}_\odot \text{ kpc}^{-2}$ (following McGaugh, 2015) and the SFR is lower than $3.0 \times 10^{-3} \text{ M}_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$ (consistent with De Donder & Vanbeveren, 2002). These values are selected as indicative of the Solar neighbourhood.

3.2 Metallicity

The basic precondition for the existence of a rocky planet is the sufficient amount of heavy elements available in the proto-planetary disc during planet formation. On the other hand, a reasonable and generally well accepted hypothesis is that a higher amount of metals in the proto-planetary disc leads to a larger probability of having gas giants. The gas giants can extensively perturb and even destroy the smaller, solid surface planets (i.e, see Lineweaver, 2001). However, the metallicity at which probability of the gas giants formation is significant for the habitability of the host stellar system cannot be determined with certainty. This is caused by observational selection effects. The giant planets are more likely observed than smaller ones and the host star atmosphere is contaminated with debris from the proto-planetary disc. In the work of Buchhave et al. (2012) it is implied that the Earth-size exoplanets form around stars with a wide range of metallicities while the giant planets are more common around high metallicity hosts. On the other side of the metallicity scale the absence of building blocks means no existence of the Earth-like habitats at all.

The metallicity is expressed as $[\text{F}_e/\text{H}]$, the F_e relative to hydrogen abundance, on a logarithmic scale where zero is the Sun’s metallicity. We adopted a Gaussian probability distribution for the metallicity dependent habitability criteria. The distribution mean value is at $[\text{F}_e/\text{H}] = -0.075$ with standard deviation (σ) of 0.1125. This way, the 2σ lower end of the selected distribution is at $[\text{F}_e/\text{H}] > -0.3$. This is the lowest metallicity in the sample of 7 well measured stellar systems with the Earth-size exoplanets (Schuler et al., 2015). The distribution is normalized so that the highest value of the probability density is 1.0. A pseudo-random number (Saito & Matsumoto, 2008) from a (0,1) interval, with a uniform density, is assigned to each stellar particle in the simulation. If the assigned number is smaller than the corresponding value of the normalized Gaussian probability density distribution, the particle is considered as a potential habitat. The results are averaged over five separate runs of our habitability analysis. The more simple case, of using a top-hat probability function instead of the Gaussian, gives similar results. The only significant difference is that the number of the potentially habitable particles is larger. This is expected since in a top-hat case all particles with metallicity higher than -0.3 represent the potential habitats.

3.3 Habitable time

One of the most important parameters for the research of the astrobiological development of a galaxy is an estimate of the time span an individual stellar system spends continuously dwelling in a habitable friendly environment. However, the simulation finite time resolution prevents from calculating habitability relevant Galactic parameters at each point of the particle trajectory. The higher the sampling rate along the particle trajectory (= smaller time step of the analysis) the higher the chances that the particle can be found in life inhospitable conditions. This means that a higher sampling rate will reduce the number of continuously habitable particles for a given biological time scale. As a consistent temporal measure of particle habitability we adopt:

$$f_{\text{ht}} = \frac{t_{\text{h}}}{a}, \quad (2)$$

where t_{h} is the number of snapshots for which the particle was found in a habitable grid cell, and a is the total number of snapshots that the stellar particle spent in the simulation. We adopted the following habitability preconditions for the stellar particles:

★) $t_{\text{a}} > 1$ Gyr and

★ ★) the particle is the potential habitat according to metallicity criteria given in Section 3.2,

where t_{a} is the age of the particle, calculated as number of snapshots that the particle spent in the simulation multiplied by the temporal resolution (time step of the post simulation analysis, τ). In the following, we will refer to the stellar particles that satisfy the above conditions as candidate habitable particles (CHPs). The stellar particle is considered habitable (HP) if in addition to conditions (★) and (★ ★) it also satisfies:

$$f_{\text{ht}} > 0.5. \quad (3)$$

The $t_{\text{a}} > 1$ Gyr condition is set so that only the particles with (on average) fully developed and biologically active planets are considered. The Hadean eon on Earth lasted for 0.6 Gyr and the oldest indirect evidence for life on Earth is dated back to the end of the Hadean and beginning of the Archean eon. Also, 1 Gyr gives enough time so the f_{ht} is less susceptible to statistical fluctuations.

To examine the consistency of our habitability time estimates, we test for the convergence of the HPs number. At 10 Gyr we plot the number of HPs (N), against the variable time step τ used in the convergence test. The selected values were $\tau = \{1000, 500, 200, 100, 50, 20, 10\}$ Myr. The test results are presented in Figure 4. The slope change on the linear scale plots clearly varies in sign (although apparently less evident on logarithmic plot). We cannot make any high probability conclusions even if smaller values for τ were to be included in the test (which will definitely have to account for much larger processing times

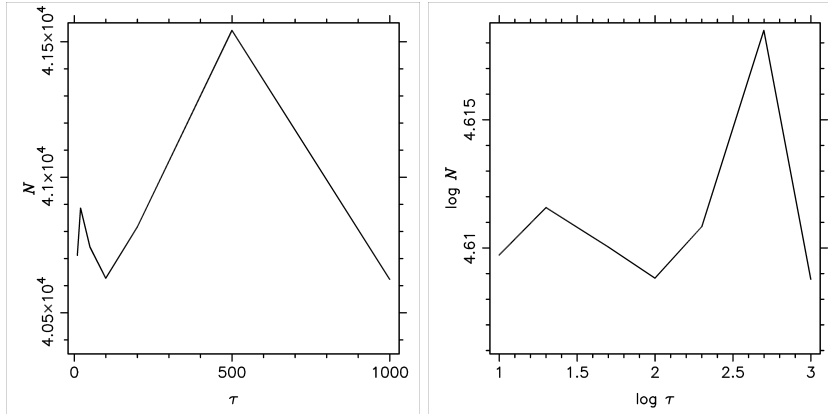


Figure 4: Number of habitable particles convergence for different time steps at the end of the simulation, 10 Gyr. Values are averaged over 5 runs.

of the simulation data analysis). However, the span of the N -axis is $\sim 2\%$ of the presented N values (even smaller when only small τ values are considered). This adds confidence to the conclusion that the constructed measure of habitability f_{ht} is robust and reliable.

4 Results and discussion

Inspection of Figure 5 shows that after the initial $\rho \sim 5$ kpc peak at ~ 5 Gyr, the 10 – 15 kpc range has the highest fractional (and absolute, Figure 6) spatial coverage with HPs at the second half of the simulated time span. From Figures 8 and 7 it is evident that distribution of HPs follows in shape the distribution of disk areas containing HPs. Following the results of Roškar et al. (2011), that emphasize outward migrations caused by dynamical friction, we make the following interpretation. The distribution peak at 5 kpc at earlier times is probably caused by the build up of stellar particles formed from dense gas areas near the bulge (Figure 3). In the second half of the simulated time span the presence of high SFR areas around $\rho = 10$ kpc likely causes the appearance of a significant number of new stellar particles. These particles are then scattered preferably to the outside of the disk, (Figures 3 and 1) contributing to the peaks of the habitable stellar mass and the habitable disk surface areas at $\rho = (10, 15)$ kpc.

From Figures 5 and 8 at 10 Gyr, $\approx 3 \times 10^6 \text{ M}_{\odot} \text{ kpc}^{-2}$ is distributed over $\approx 40\%$ of the grid cells (for 10 – 15 kpc range) and $\approx 1.5 \times 10^6 \text{ M}_{\odot} \text{ kpc}^{-2}$ is distributed over 20% of the grid cells (at ≈ 5 kpc). This gives $\approx 7.5 \times 10^6 \text{ M}_{\odot} \text{ kpc}^{-2}$, which translates to $\approx 7.5 \text{ M}_{\odot} \text{ pc}^{-2}$ as the average surface density of the habitable stellar mass in the habitable disk areas. This value is somewhat

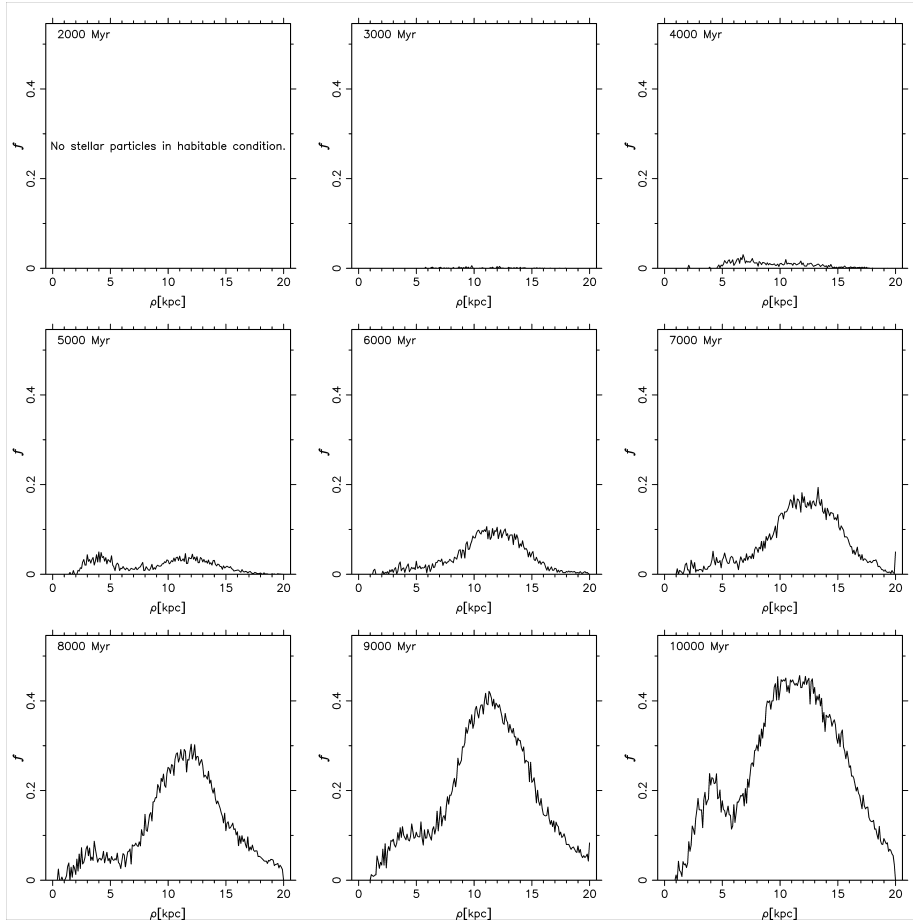


Figure 5: Distribution of fraction of the habitable grid cells (containing at least one HP) at a given radius ρ . Averaged over 5 runs.

higher than the lowest value for the stellar component density on Figure 1 ($5 \text{ M}_{\odot} \text{pc}^{-2}$). It follows that for a better insight in the distribution of the habitable stellar mass, at the disk areas with small stellar density, such as the outskirts, a higher mass resolution of the simulation is required.

4.1 Limitations of the model

While there are indications that late-epoch baryonic infall plays a significant role in realistic star-formation histories of any large spiral galaxy on both theoretical and observational grounds (e.g., Ferguson & Clarke, 2001; Bregman, 2007; Prodanović & Fields, 2008), there are several justifications for not including this infall in the present simulation. First and foremost, together with

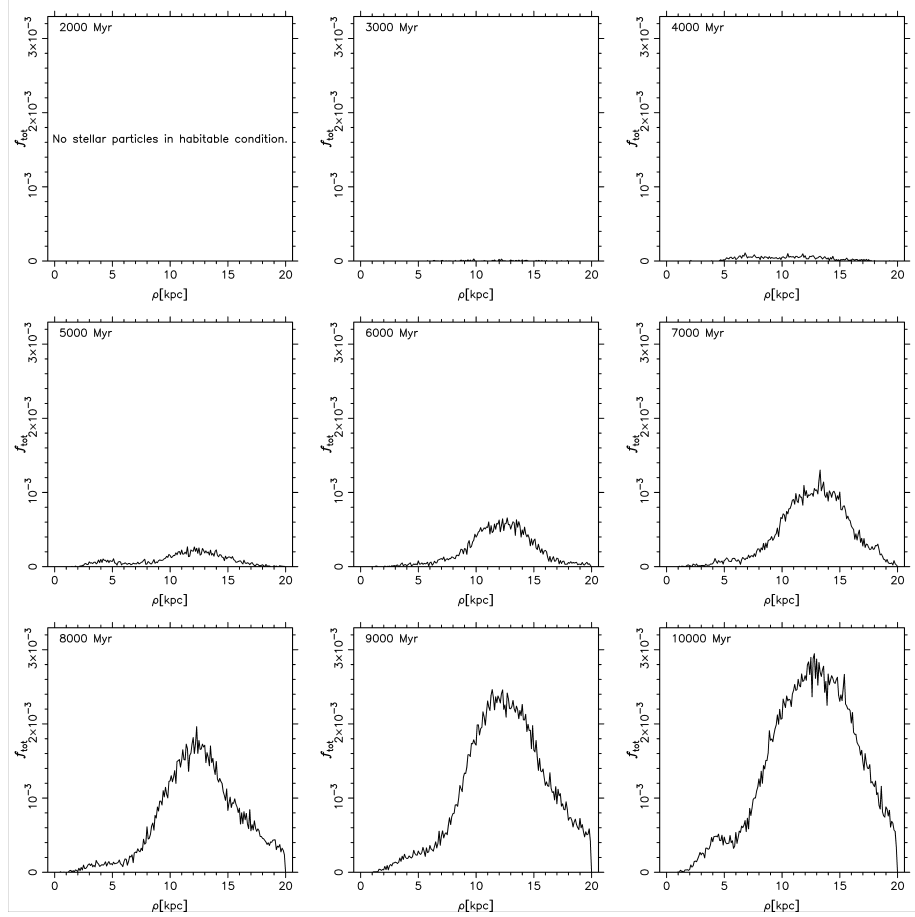


Figure 6: ρ distribution for the fraction of the habitable grid cells (containing at least one HP) from total number of grid cells for $\rho < 20$ kpc. Averaged over 5 runs.

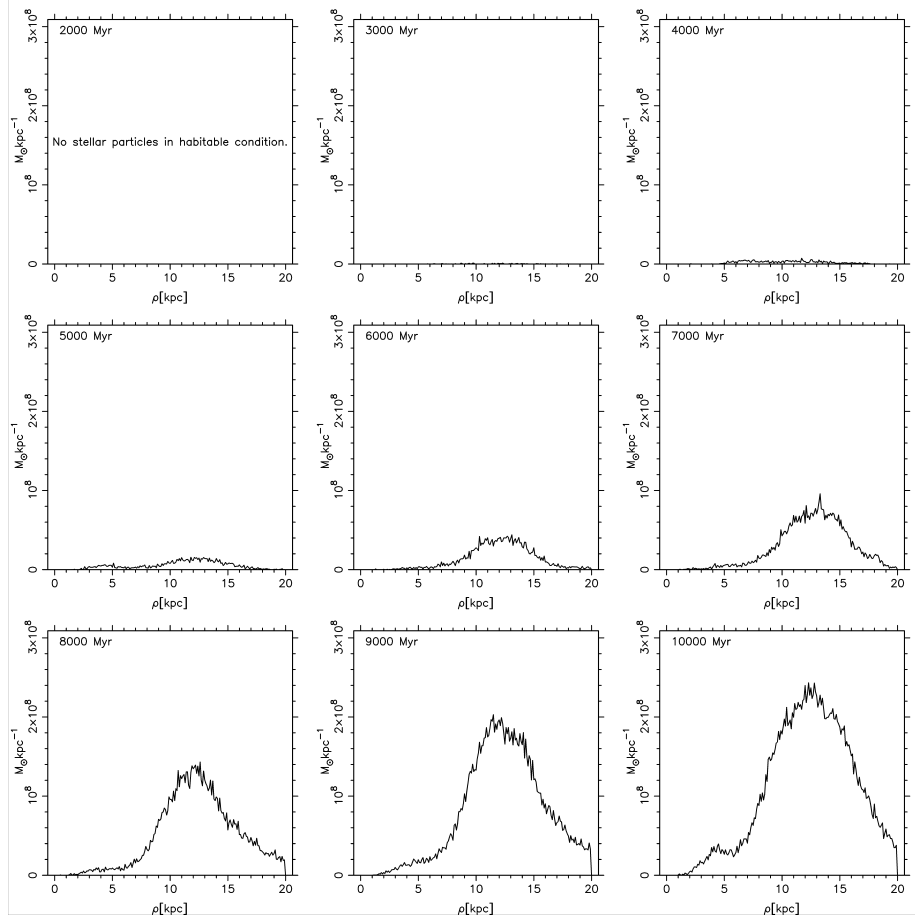


Figure 7: Habitable stellar mass (particles) per unit galactocentric distance. Averaged over 5 runs.

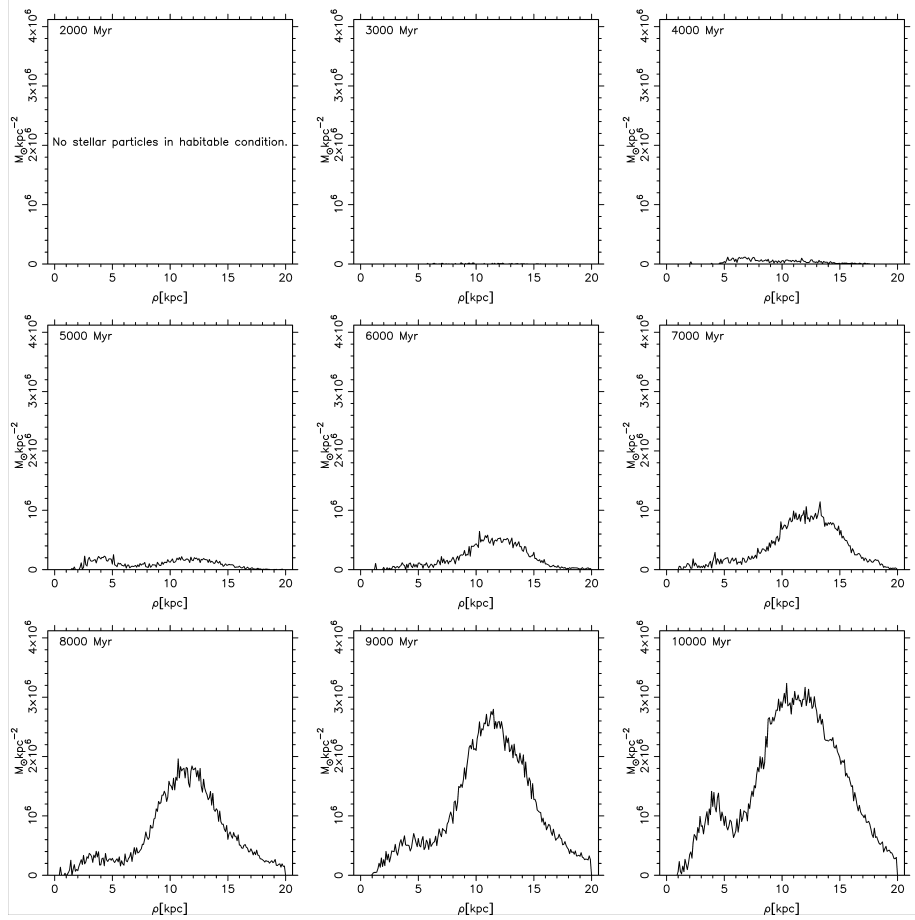


Figure 8: Surface density of habitable stellar mass (particles) averaged over angular coordinate in the plane of the disk for a given ρ . Averaged over 5 runs.

results in Forgan et al. (2015), this is the first use of cosmological simulations of galaxy formation for astrobiological purposes, and it makes sense to make it as simple baseline case as possible. It is necessary to get at least some hold on the simplest, unperturbed case and its effective dynamics before proceeding to more complex perturbed histories. Second, we are dealing with a typical $\sim L_*$ spiral galaxy whose infall/merger history is unknown in advance, and the late infall is quite a complex process due to its intermittent and stochastic nature, immensely complicating the numerical task at hand. The fact that the infall history of the Milky Way is somewhat better understood prompts an astrobiologically important question how typical is Milky Way’s star formation history in comparison to other similar systems (Kruijssen & Longmore, 2013). Third, suppression of star-formation below $z \simeq 0.5$ noted in IR surveys of Milky Way-like galaxies (Papovich et al., 2015) coupled with the quenched star formation in infalling dwarfs in the ViaLactea II simulations (Rocha, Peter & Bullock, 2012) taken together suggest that the impact of late infall on the astrobiologically interesting population of metal-rich disk stars is not large on the average. That said, an important future task for this kind of simulations, concurrent with increasing resolution, is to simulate such infall and its effects on radial mixing in particular.

4.2 Comparison with other studies

The present model results are in discrepancy with the studies of Gowanlock, Patton & McConnell (2011) and Morrison & Gowanlock (2015), who obtain much more centrally concentrated GHZ. While the exact reasons will require a separate study to ascertain, we find that one or more of the following played an important part in creating the discrepancy: **(i)** the model of Gowanlock, Patton & McConnell (2011) applies specifically to the Milky Way, and uses a semi-analytic stellar density and star-formation history models specifically geared toward the local observations. In contrast, the present study like the one of Forgan et al. (2015) uses a full numerical treatment of a *Milky Way-like* giant spiral galaxy. **(ii)** The metallicity gradient of Naab & Ostriker (2006) used by Gowanlock, Patton & McConnell (2011) is shallower than the effective metallicity gradient obtained in the cosmological simulations, and is shallower than the best-fit global gradient obtained by Rocha-Pinto et al. (2000) and Tadross (2003). The results of Rocha-Pinto et al. (2000) were used in Vukotić & Ćirković (2012). **(iii)** As Gowanlock et al. (2011) correctly note, their model does not take into account other mechanisms for decreasing habitability operational mostly in the inner parts of the disk/bulge of the Milky Way, notably dynamical disruption of stable planetary orbits, chemical evolution overshooting resulting in oceanic “super-Earths”, ambient UV suppression of dust grains necessary to form habitable planets, rare, but extremely important γ -ray burst sterilizations, and even indirect effects such as the cosmic-ray flux-climate connection. Note that all these processes are likely to make the inner parts of the Galaxy less habitable than hitherto suspected.

4.3 (A)typical Earth

For a more detailed analysis, the t_h distribution of CHPs is examined. How typical is the Earth among habitable planets of similar age and f_{ht} ? In this modest attempt to answer this formidable question we have constructed Figure 9 and Table 1. In Table 1 we give the distribution of CHPs number over f_{ht} and age. The peak values for each given age are in bold font; We deliberately disregard the values for $f_{ht} < 10\%$ since it is evident from Figure 9 and their low f_{ht} that those particles are likely members of bulge population with low prospects for habitability. The CHPs that spent almost all of their life time in the habitable friendly conditions reside at ~ 16 kpc from Galactic centre and are ~ 3 Gyr old (Figure 9). A typical Solar system analog, 4 – 5 Gyr old at 8 – 10 kpc from Galactic centre, has the highest probability for $f_{ht} \sim 50\%$ (Figure 9 and Table 1). As the value for f_{ht} gets higher the probability peak moves to higher ρ . At $f_{ht} \geq 90\%$ less than 1% of the systems (that are 4 – 5 Gyr old) can be found to reside at 8 – 10 kpc from Galactic centre (Figure 9 and Table 1). For smaller values of f_{ht} this fraction is likely to be as high as $\sim 10\%$. The highest value in bold typeface from Table 1 is for particles with $30\% < f_{ht} < 40\%$ old between 8 and 9 Gyr. From Figure 9 it is evident that these particles are the most numerous at $\rho < 10$ kpc distance from Galactic centre. Summing up the values in Table 1 (without the values in $f_{ht} < 10\%$ row), a typical CHP in the galactic disk has $\sim 35\%$ chances to be habitable ($f_{ht} > 50\%$). With $f_{ht} < 10\%$ row included, chances drop to $\sim 20\%$. This indicates the importance of SFR, stellar density and dynamics for the regulation of Galactic habitability.

4.4 Wider GHZ?

Figure 5 implies that areas in the 10 – 15 kpc range have the highest probability of containing habitable systems and although the same order of magnitude habitability exists for most of the ρ range, the area between 10 – 15 kpc should be favoured in terms of habitability. This complies with the results on Galactic habitable zone in Peña-Cabrera & Durand-Manterola (2004), where the zone of enhanced habitability probability is estimated to be at $\rho = (4, 17.5)$ kpc. Our results differ from $\rho = (7, 9)$ kpc conservative estimates in Lineweaver, Fenner & Gibson (2004) probably caused by calibrating threshold habitability values of SFR and stellar density to Solar neighbourhood. Also our zone of enhanced habitability does not simply drift to the outskirts of the disk with time (as also suggested in Gonzalez, Brownlee & Ward, 2001) but rather have a rapid build-up at $\rho = (10, 15)$ kpc after 5 Gyr, caused by dynamical friction effects that scatter gas and stars away from the Galactic centre. In more realistic cases, these effects might be partially balanced by minor mergers, resupplying the central regions with gas and stars, which remains an interesting topic for future studies.

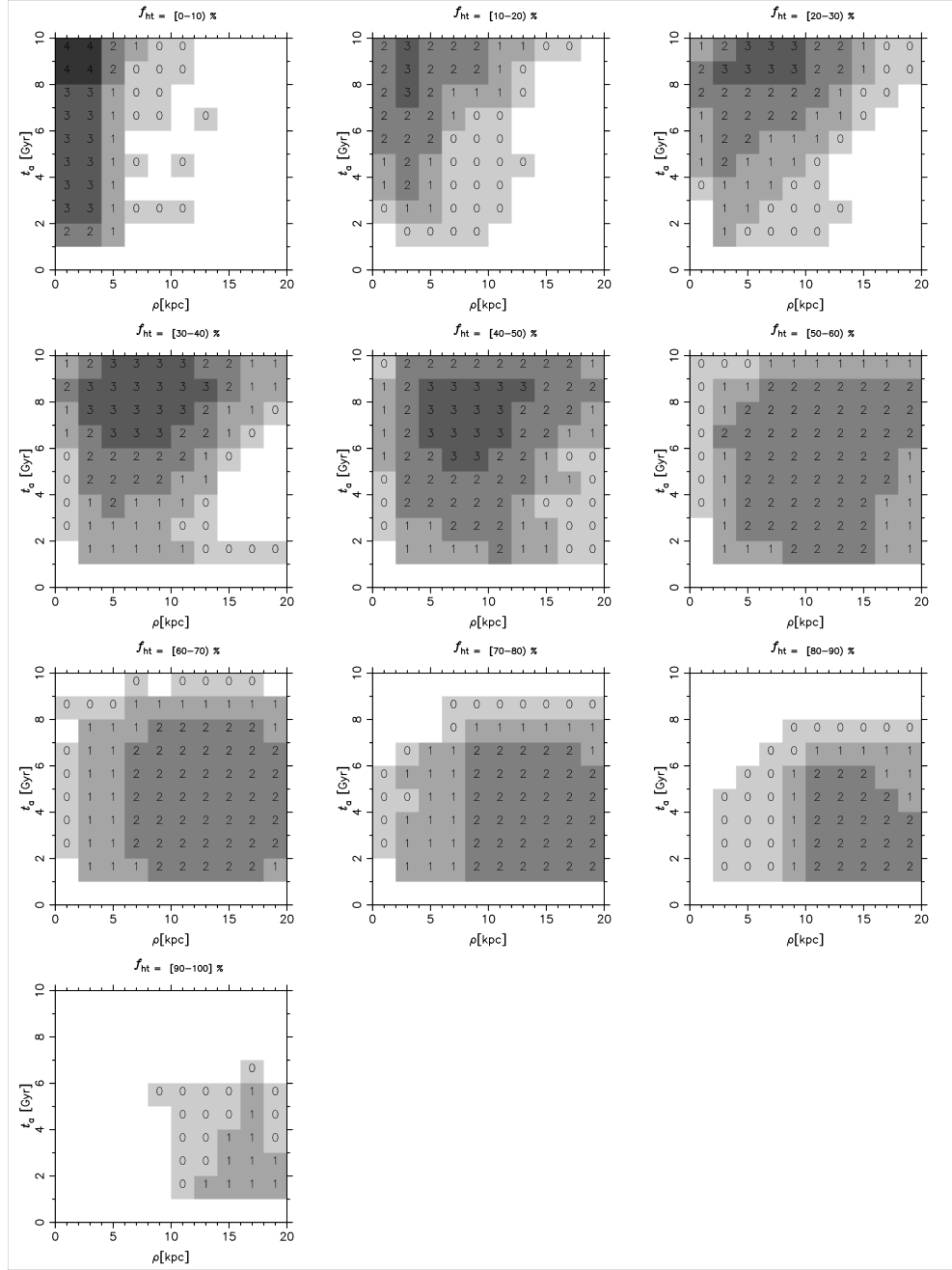


Figure 9: CHPs distribution over ρ and age for various f_{ht} (intervals indicated in each panel). The numbers are presented in order of magnitude form as both, shades of gray and digits; Values $[0, 10)$ with 0, $[10, 100)$ with 1, $[100, 1000)$ with 2, $[10^3, 10^4)$ with 3 and $[10^4, 10^5)$ with 4. Averaged over 5 runs.

Table 1: Number of CHPs distributed over f_{ht} and ages averaged over 5 runs. Values in bold type face are maxima for the given column, excluding values in (0-10) % row.

$f_{\text{ht}}[\%]\backslash\text{Gyr}$	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
0-10	935	1413	1863	1707	2018	3186	7003	14781	55387
10-20	11	44	165	383	582	823	1258	2142	1355
20-30	23	46	120	225	453	857	1740	4651	4039
30-40	79	90	254	598	1342	3028	6642	12694	6403
40-50	303	434	1048	1964	3140	4291	5647	5996	1729
50-60	933	1033	1669	2035	2580	2875	2369	1494	296
60-70	1603	1840	1999	1986	2115	1755	1003	333	7
70-80	1789	1735	1582	1468	1190	728	181	20	0
80-90	1004	901	860	648	416	101	19	0	0
90-100	139	55	37	36	23	2	0	0	0

4.5 Contact prospects

These findings shed a new light on the importance and relevance of the GHZ concept on our astrobiological and SETI studies. In contrast to the simplistic approach of the early work on Galactic habitability, it seems now that whatever metric of habitability is adopted, the distribution over spatial locations and temporal history will be complex, with much hitherto unnoticed medium- and small-scale structure. Moreover, it could be expected that future higher-resolution studies will reveal still more structure on smaller scales. In contrast even to more sophisticated models based on chemical evolution (e.g. Spitoni, Matteucci & Sozzetti, 2014), we perceive a higher fraction of the habitable set on higher galactocentric distances, beyond 10 kpc.

This might be in accordance with several alternative hypotheses suggested in SETI studies. In particular, regions further out in the Milky Way disk might be better targets for practical search programmes than previously suspected (cf. Ćirković & Bradbury, 2006). To what extent is the realistic GHZ porous enough to leave larger "persistent" bubbles capable of explaining Fermi's paradox (Landis, 1998; Kinouchi, 2001), remains to be seen in future work of higher resolution.

At $0.9 < f_{\text{ht}} < 1$ panel in Figure 9 it is likely for a planet with the highest chances of habitability to be younger than Earth instead of being older (as suggested in Lineweaver, 2001). This is in accordance with our perceived absence of contact with extraterrestrials (with the usual assumptions of realism, scientific naturalism, and gradualism, cf. Ćirković, 2009). Absence of the contact was also explained, due to influence of habitability agents, by arguments of astrobiological phase transition resulting from an expected decrease in SFR (see Vukotić & Ćirković, 2012). In our model SFR sharply decreases after 3 Gyr which makes the results of this paper even more appealing in explaining the lack of perceiving aliens so far.

The simulations performed here are similar to ones recently reported by Forgan et al. (2015), including very similar mass resolution ($5 \times 10^4 M_\odot$ vs. $3.16 \times 10^4 M_\odot$) for stellar particles, and consequent low spatial resolution. Many caveats systematically presented by Forgan et al. apply here as well, notably the impossibility to treat individual sterilization events due to local supernovae with the state-of-the-art resolution. The present model introduces the notion of continuous habitability, which changes its results somewhat in comparison to those presented in particular in Figure 7 of Forgan et al. (2015). On the other hand, it is important to note a general similarity between results on the Milky Way habitability obtained in two independent studies, especially when it comes to the seemingly counter-intuitive conclusion that outer edges of the Galactic disk are more habitable than hitherto assumed. Clearly, future improvements in both resolution and adding further dynamical mechanisms (spiral-arm crossings, Galactic tides stemming from vertical oscillations, γ -ray bursts, etc.) will further constrain habitability and offer more meaningful target selection for observational searches.

5 Summary

We present an isolated Milky Way simulation in GADGET2 N-body SPH code to model the habitability of Galactic disk in order to assess the question of perception of Earth-like extraterrestrial habitats. The peak values for possibly habitable stellar mass surface density move from 10 to 15 kpc galactocentric distance in 10 Gyr simulated time span. The stellar particles that spent almost all of their life time in a habitable friendly conditions reside at ~ 16 kpc from Galactic centre and are ~ 3 Gyr old. Stellar particles that are $4 - 5$ Gyr old with $f_{\text{ht}} \geq 90\%$, are also predominantly found in the outskirts of the Galactic disk. Less than 1% of these particles can be found at a typical Solar system galactocentric distance of $8 - 10$ kpc. Although we include the effects of Galactic dynamics in our model our results appear strongly dependent on distributions of SFR and stellar density resulting from our simulation and imposed habitability criteria. Examination of this dependence is a viable scope for future studies and projects that will model changes in SFR and stellar density parameters caused by interaction of a Galaxy with its environment.

We argued in favour of a hypothesis that any practical search for other Galactic complex biospheres/extraterrestrial civilizations should be steered towards the outskirts of the Galactic disk and stellar systems younger than ours. This is in accordance with our present lack of SETI results. We may not be alone out there after all, but we are older than they are. The room for future studies, both observational and numerical is wide open (both literally and metaphorically).

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